Manufacturing Demonstration Facility Overview

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
ADVANCED MANUFACTURING OFFICE

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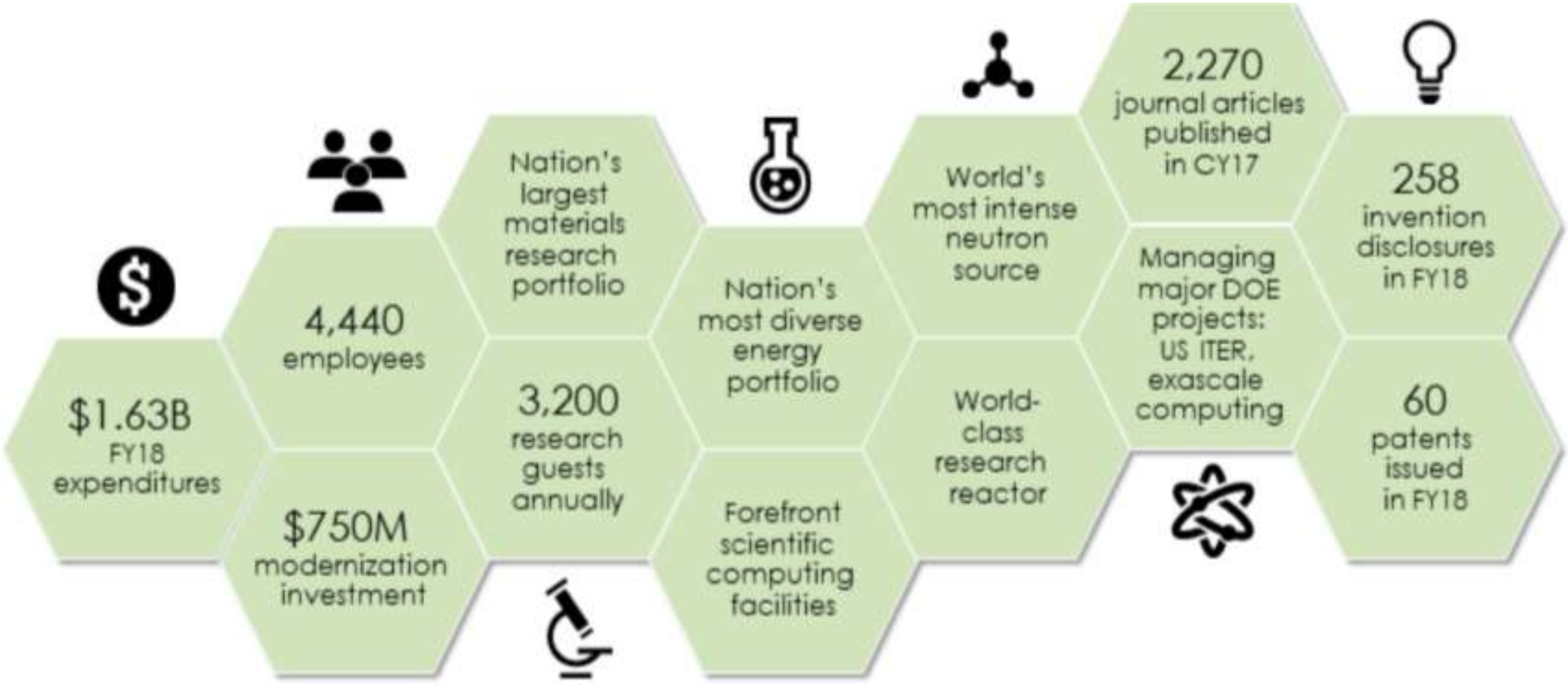
Leveraging ORNL's Capabilities to Advance Mfg.

Neutron Scattering: SNS & HFIR

- World's most intense pulsed neutron beams
- World's highest flux reactor-based neutron source

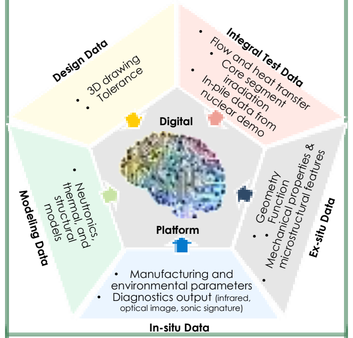
Leadership-Class Computing: Titan

- Nation's most powerful open science supercomputer
- Application development, software & hardware technology, Exascale systems



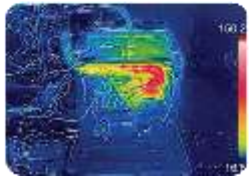
Nuclear Research & Advanced Mfg.

- Manhattan Project, 75 years of nuclear research
- Radioisotope projection, fusion and fission



Advanced Materials

- DOE lead lab for basic to applied materials R&D
- Technology transfer: billion dollar impacts



ORNL's Advanced Manufacturing Program

Facilities

- Carbon Fiber Technology Facility
- Manufacturing Demonstration Facility
- Roll to Roll Processing / Battery Manufacturing Facility

Projects

- DOE-AMO Lab Led Projects
- DOE-AMO Industry Led Projects
- Combined heat and power
- Strategic Partnership Program Projects
  - Other Federal Agencies
  - Private Business

Multi-party consortiums

- Critical Materials Institute
- Roll to Roll Consortium
- CEMI and NNMI Institutes, Hubs, MDFs and Initiatives
- Research Projects Between Labs
- Mission Innovation

Tech to market

- MDF Technical Collaborations
- Small business vouchers
- Innovation Crossroads
- TN REV program
- Technologists in residence
- Better Plants & Technical Assistance

Partnering with industry, small business, universities and others to:

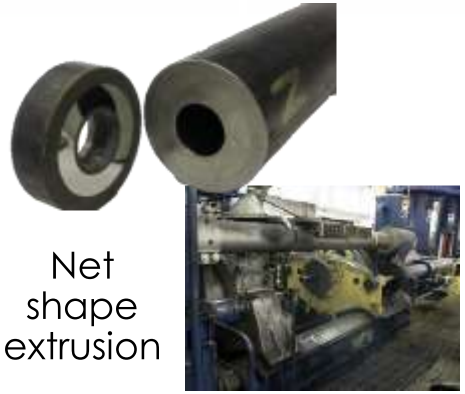
- Develop and commercialize targeted technologies
- Reduce life-cycle energy consumption of next generation products
- Encourage continuous improvement in corporate energy management
- Enhance US competitiveness

Building on a strong base of materials and manufacturing capabilities

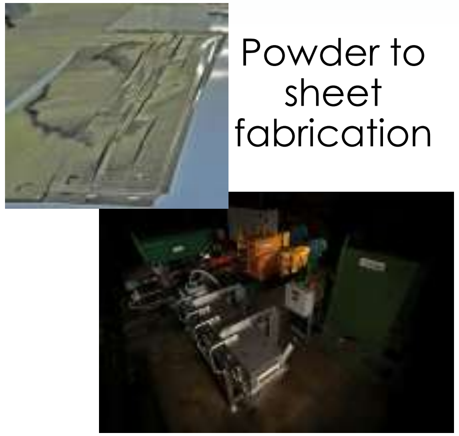
Novel materials			Advanced processing		
Powder metallurgy	**Casting and computation**	**Extrusion/process development**	**Direct roll compaction**	**Isothermal/ shear rolling**	**Infrared processing**
• New reduction technologies • Affordable consolidation development • Net shape fabrication	• E-beam, arc, induction, plasma • High-strength, low-density component fabrication • Porosity evolution and grain refinement	• Piping and tubing • High yield aircraft long forms • Energy-efficient mill product	• Low-cost Ti sheet • Composite armor • Heat exchanger plates and desalination	• Improved formability of Ti and Mg sheet and plate • Cladding of lightweight metals • Energy-efficient rolling practices	• High density Infrared • Pulse thermal processing • Direct write capability

F-35 component forging from powder

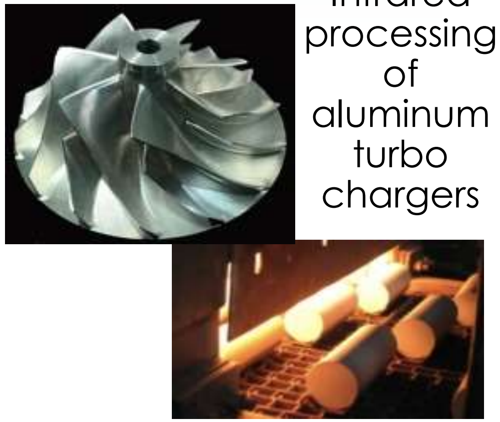
Reduced porosity casting control arm



Net shape extrusion



Powder to sheet fabrication



Infrared processing of aluminum turbo chargers

Advanced Manufacturing Facilities: Engaging with Industry

Manufacturing Demonstration Facility

- Public-private partnership engaging industry with national labs
- Focused on AM and composites
- Over 30 adv. mfg. systems

Carbon Fiber Technology Facility

- Capacity of up to 50 tons/yr.
- Low cost feedstock for CF production
- Applications include vehicles, wind, compressed gas, other DOE initiatives

Battery Manufacturing Facility

- Country’s largest open-access battery mfg. R&D center
- Developing low cost mfg. processes
- Establishing domestic supply chain of adv. batteries

The Manufacturing Demonstration Facility

An ORNL User Facility focused on cost-shared early-stage applied R&D in the areas of additive manufacturing and carbon fiber materials research related to energy

Mission driven to reinvigorating US manufacturing

Diversity in various technology areas

Embraces technical & scientific risk

Colocation of staff, industry partners and academia

Core R&D	Industry Collaborations	Education and Training	Demonstrations
R&D in materials, systems, and computational applications to develop broad of additive manufacturing	Cooperative research to develop and demonstrate advanced manufacturing to industry in energy related fields	Internships, academic collaborations, workshops, training programs, and course curriculum for universities and community colleges.	Executing on "moon shot" demonstrations to integrate partners, understand technical challenges, and accelerate technologies.

Position	No.
Researchers	**40**
Technicians	14
Support Staff	10
Post Graduates	17
Students	69
Guests & Internships	44
Total	194

Staff, intern, student, and industry performing research on over 50 current projects that serve a wide range of energy and manufacturing needs.

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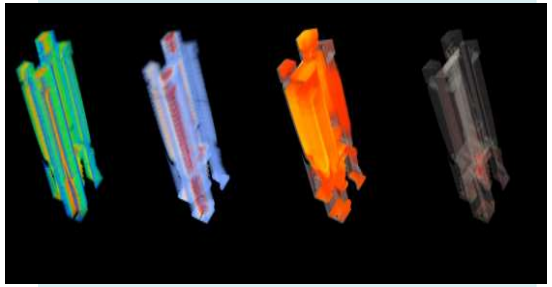
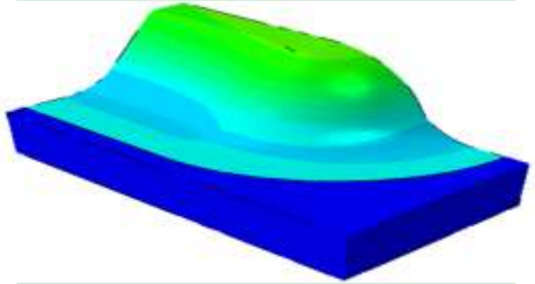
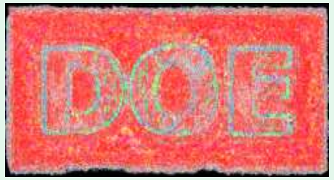
High Potential, Early-Stage R&D for Advanced Manufacturing

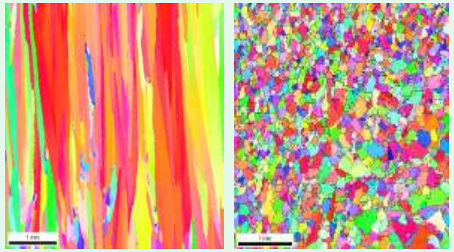
	Materials	Qualification and Certification	Modeling and Characterization	Systems
Challenges	• Costly material feedstocks • Limited materials • No AM-developed materials • Post-processing required • Microstructure engineering through precise process control and monitoring	• Limitations in conventional metrology • Required materials specifications & practices • Costs in certification • Variability of process	• Complex temporal-spatial process • Lack of understanding on impact of local microstructure • Warping • Anisotropic properties	• Limitations in build volumes • Slow processing • Reliability • Limited sensor employment • No closed loop control • Improved reliability
				
R&D Solutions	• New metallic alloys and polymers designed for AM • Spatially graded & hybrid materials • Understanding the role of feedstock	• In-situ process monitoring • Filters and correlative data analysis • Machine learning and uncertainty quantification • Integration and deployment of rapid qualification tools	• Development, implementation and validation of AM-specific workflow • Crystallographic & 3D tomographic information • Physics-based simulations • In-situ non-destructive evaluation and post processing metrology techniques	• Pick and place/hybrid • Expansion of materials • Large-scale/fast rates

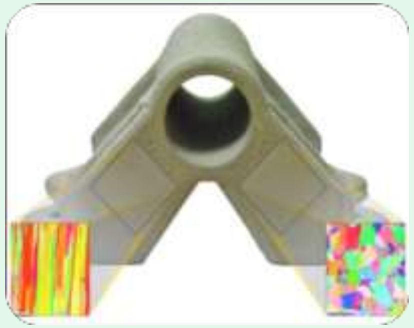
Materials for High Performance AM Components

High Temperature Nickel Alloys and Refractories

Location Specific Control Over Microstructure

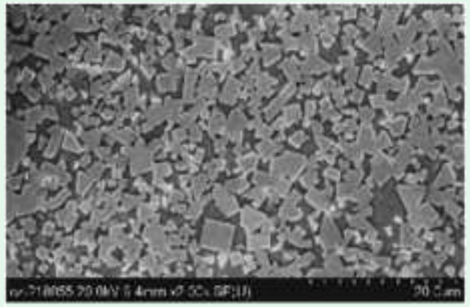




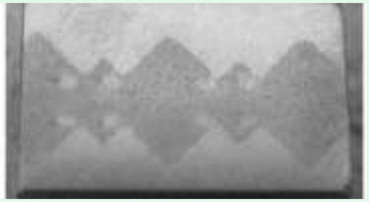


Advanced Steels

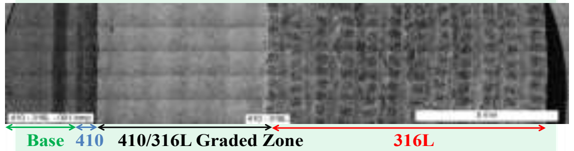
Hybrid Materials, Composites, and Graded



Micrograph of binder jet, sintered WC-Co



AM/PM of Ti-6Al-4V and TiC/TiB_2 composite

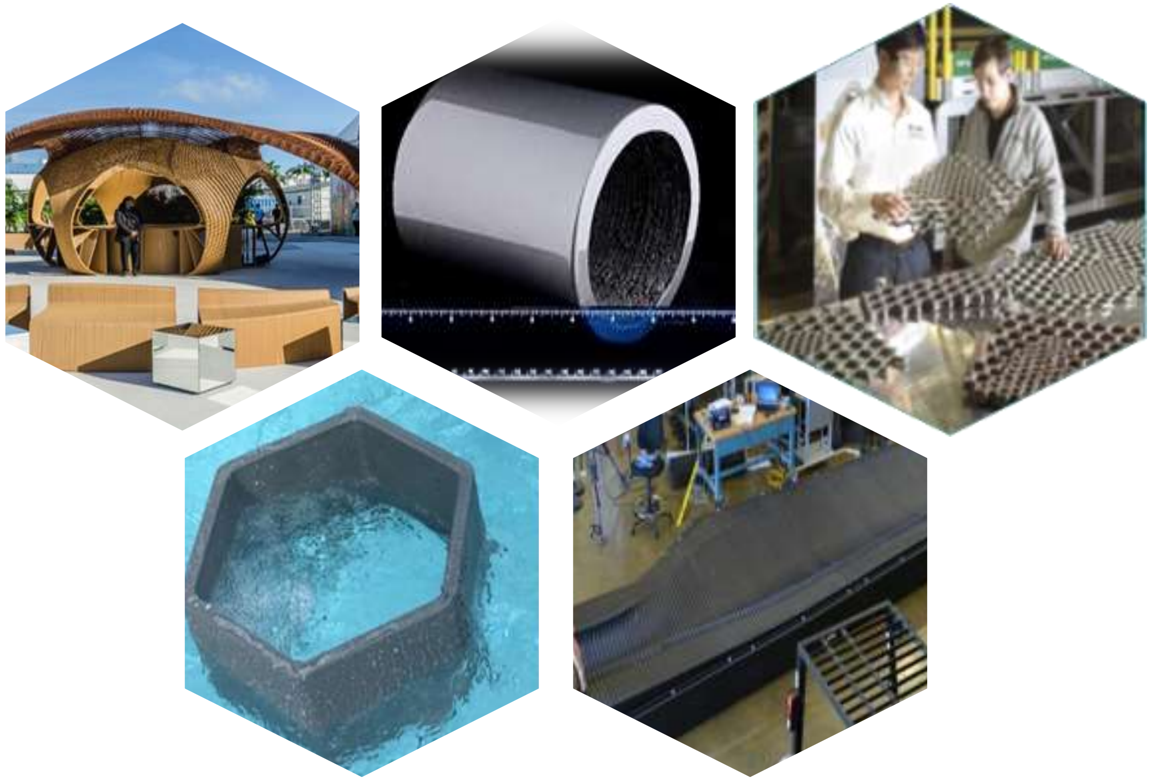


Graded transition joints

Over 50 Metal and Metal Matrix Composite Combinations Printed

Big Area Additive Manufacturing

AM of thermoplastics and composites



Over 75 Reinforced Polymer Material Combinations Printed

- Large-scale bio-derived structures
- 3D printed rare earth magnets
- Foams between 0.2 to 0.8 g/cm^3
- Room- and high- temperature composites
- Developing Thermosets with MVP Printer

"Born Qualified" Approach on Evaluating AM Components

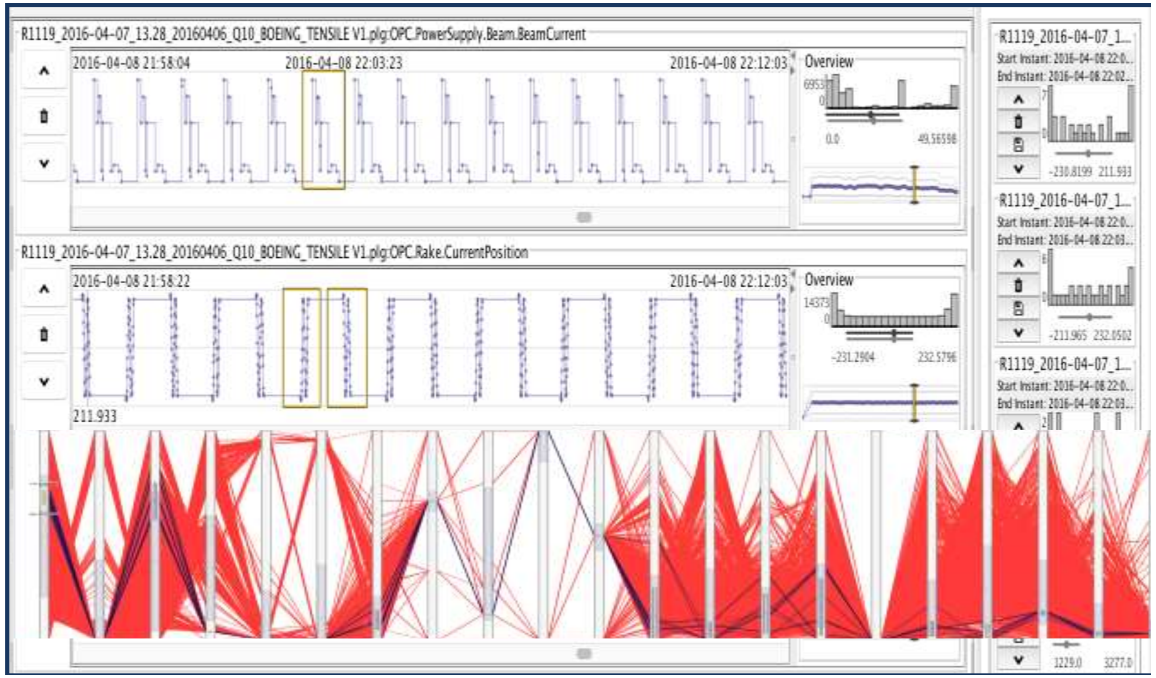
Qualification Framework for Additive Components

Creation of a 3D data framework for Additive Manufacturing
- Utilizing DREAM3D in collaboration with AFRL
- Independent of size scale, material or deposition technology

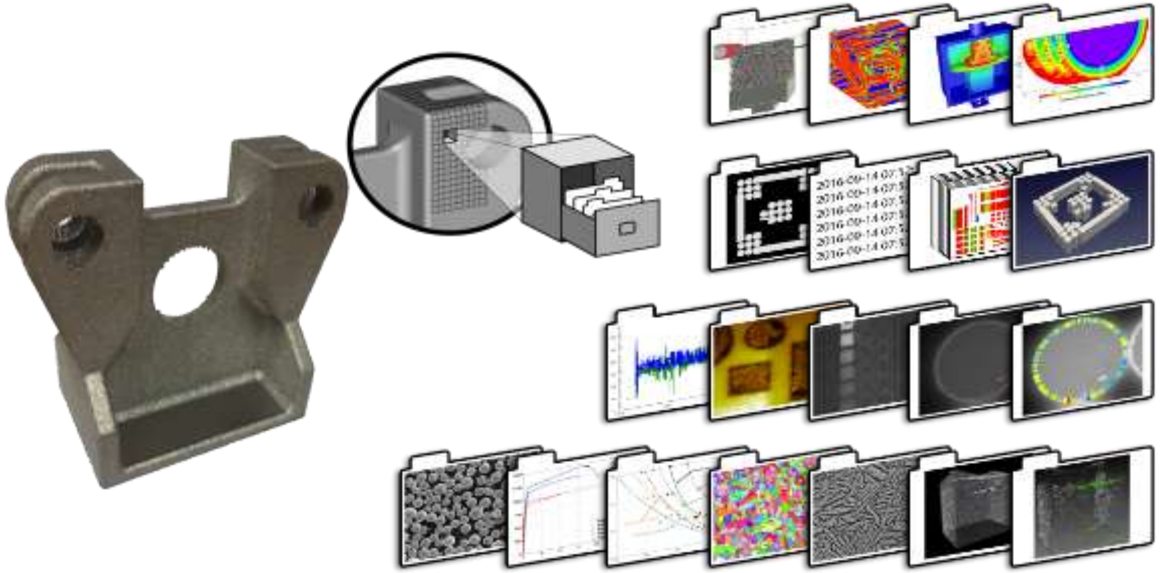
Software tool development
- Broad dissemination of tools to help users understand process variables which govern material quality
- Visualization and statistical correlation methodologies

Certification with Industry
- Novel data driven construct for certification of AM processes as opposed to individual parts: Built-certified components

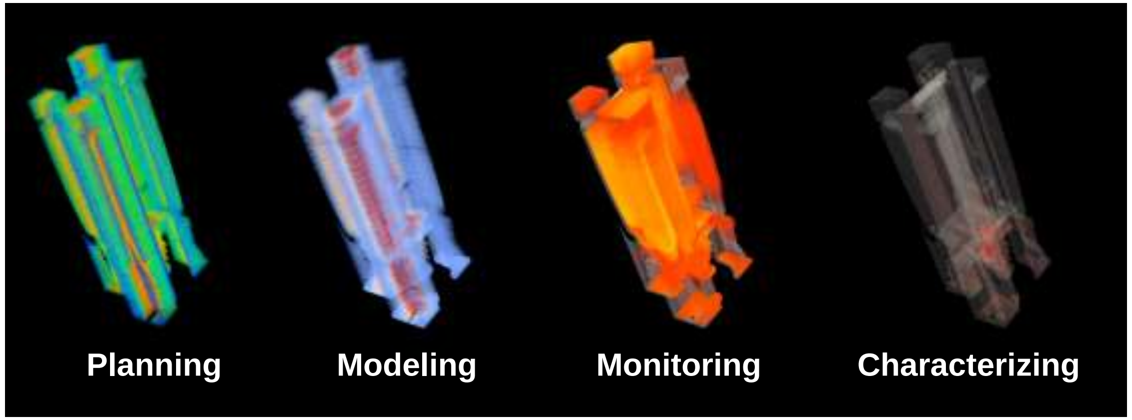
New Software Programs to Visualize AM Data



Ability to log data into a 3D Structure, Temporally and Spatially

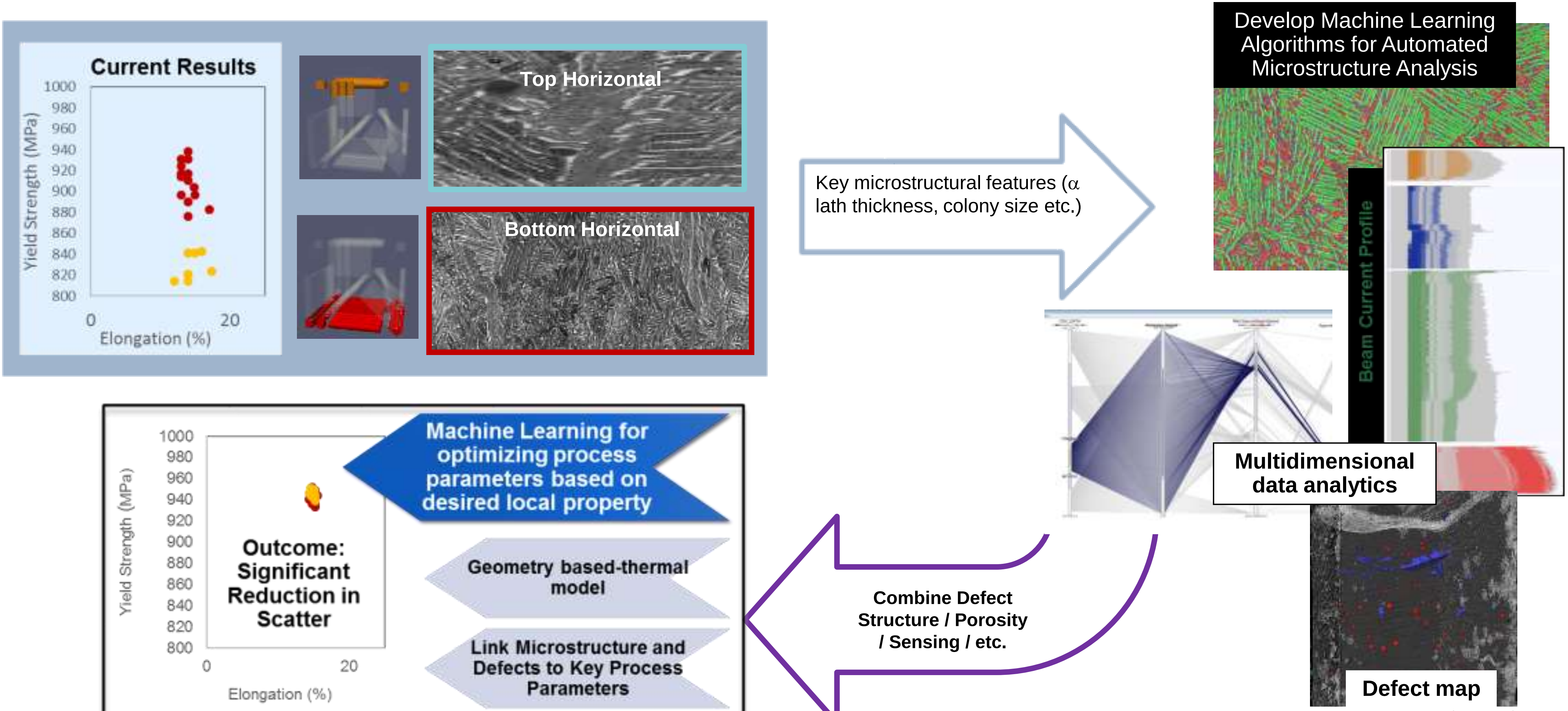


Create a Digital Twin of the Component Fabricated to Evaluate Health of the Part



Uniform, Defect-Free Microstructures through AI / Machine Learning

Applying standard processing conditions (scan strategy, energy inputs, etc.) to AM builds of different geometries will result in components with different microstructures, defect structures, and mechanical properties at different locations

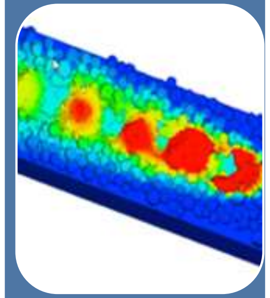


Source: Ross Cunningham et al.

Oak Ridge National Laboratory

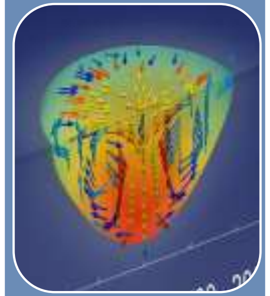
Simulation of the Processes at Various Scales

Micro-structure models (Phase Field, CA)

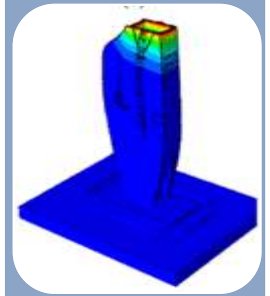


Powder scale models

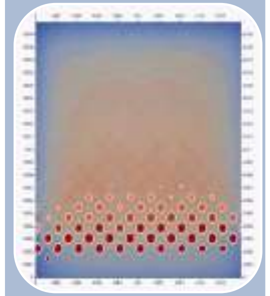
(DEM, FVM)



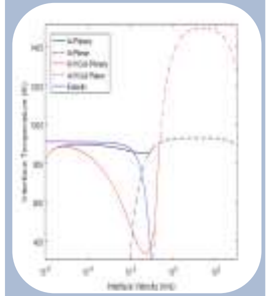
Continuum scale models (FEM, FVM)



Thermo-mechanical modeling (FEM)

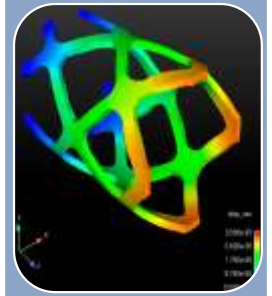


Reduced-order models (Analytical methods, surrogate models)



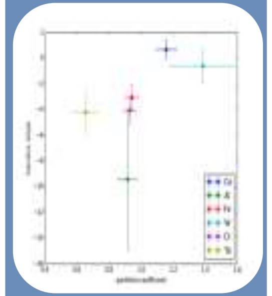
Materials theory

(CET, Interface response functions)

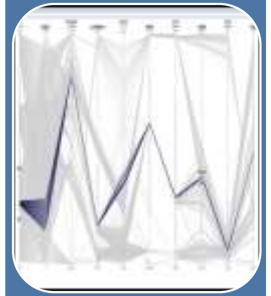


Mechanical design for AM

(Topology optimi-zation)



Experimental data, uncertainty quantification, and validation



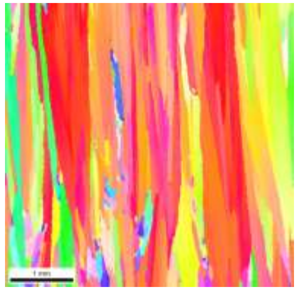
Data analytics, process design, and process optimization

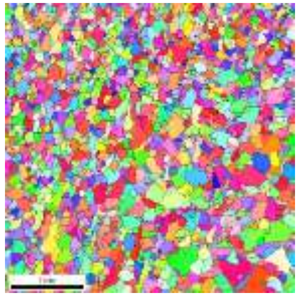
Model Development and Integration

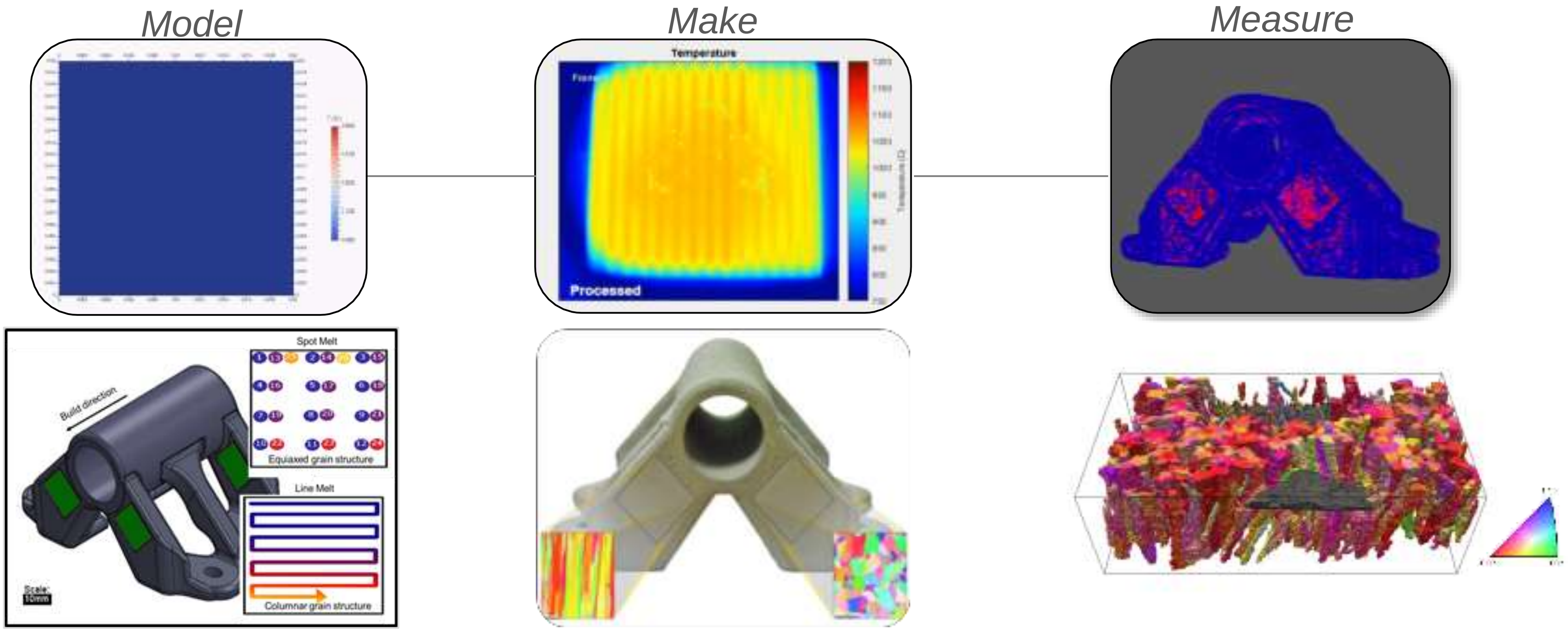
Localized Control of Mechanical Performance

Location specific control over the microstructure has been demonstrated in AM Components

- New scan strategies are being developed based on physics based modeling of material properties and thermal fields during deposition
- Unprecedented ability to control the microstructure and material properties over conventional processing technologies
- Co-optimization of multiple material properties: tensile, fatigue, creep, corrosion, etc. can be simultaneously optimized
- New design methods and models to effectively take advantage of the new controls







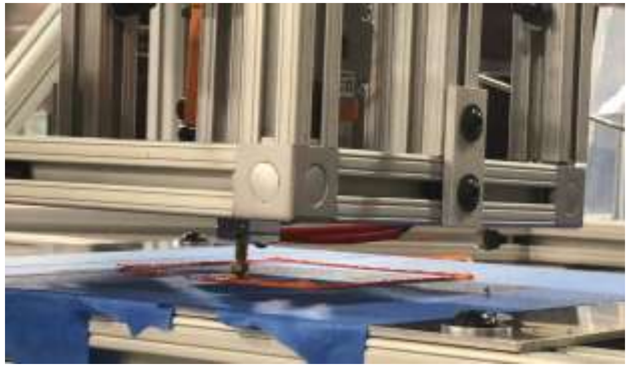
Michael Kirka, Kinga Unocic, Narendran Raghavan, Frank Medina, Ryan Dehoff, Suresh Babu. “Microstructure Development in Electron Beam-Melted Inconel 718 and Associated Tensile Properties”. Journal of the Minerals, Metals & Materials Society. Vol. 68, 3 (2016)

Developing Large-Scale Additive Machines

Cincinnati System
- 8’ x 20’ x 6’ build volume
- Up to 100 lbs./hr.
- Pelletized feed replaces filament reducing cost up to 50%

MVP System
- 16’ x 8’ x 3.5’ build volume
- Prints up to 50”/second depending on material
- 4 axes + coordination with pumping system

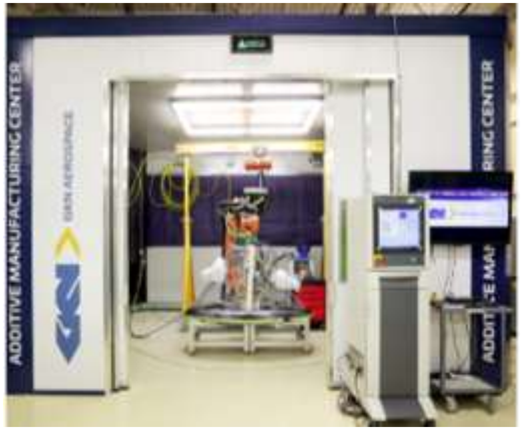
Ingersoll System
- 100’ x 40’ x 20’ build volume
- Will print up to 1000 lbs./hr.



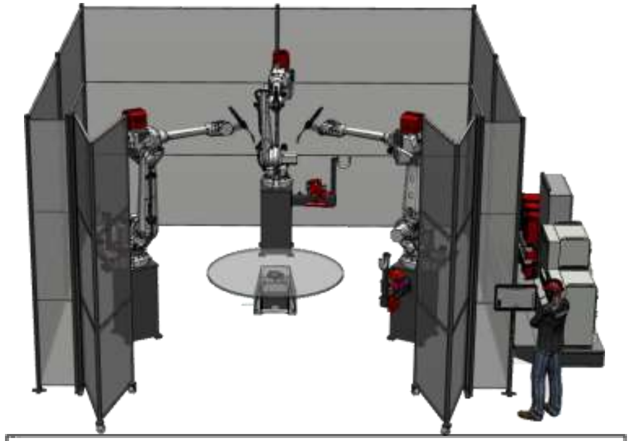
Future Concrete Systems
- Highly Deployable
- Versatile Volume Builds
- Low Cost Materials

Wolf Robotics System
- Fewer limitations
- MIG welding arm with 6 DOF
- Lost-cost feedstocks

America Makes Hybrid System
- Laser powder and wire feedstock system
- Working with advanced materials such as 410ss



GKN Aerospace System
- High-yield parts
- Net-shape titanium fabrication
- In-situ process monitoring

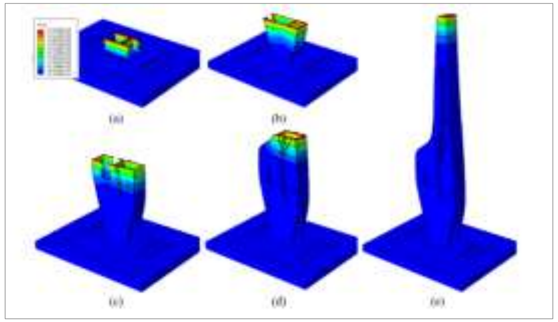


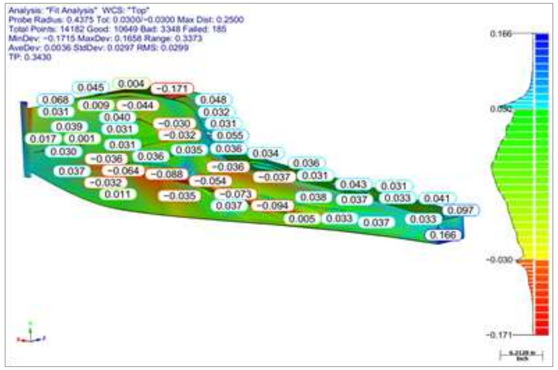
Future Metal Additive Systems
- Additive / Subtractive w Machining Capability
- Pick and Place Capability
- Multi-head, multi technology
- Digital Thread for Machine Learning and Automation

Large Scale Metal Additive Manufacturing

AM System for Steel

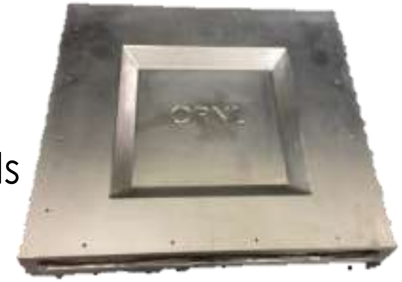
Wolf Robotics MIG Wire Additive System



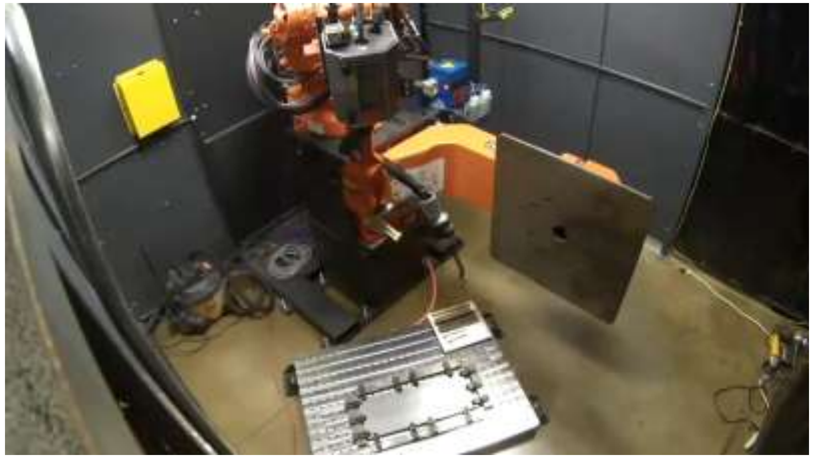


ORNL is developing Large Scale Metal 3D Printing

- Fast deposition: multi-deposition technologies being developed
- Geometry control: simulation tools and machine controls
- Graded structures: multi-material feed
- Low Cost Feedstocks



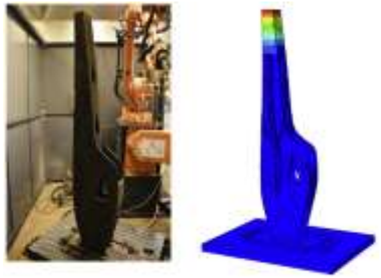
Steel Tooling



Technical Achievements from Partnerships in the Last Year

Strangpresse **licenses** ORNL extruder technology

Development of thermal mechanical models to **predict distortion and thermal history** of large-scale steel structures.



Achieved **97%** density of H13 injection molded tool with part consolidation within **3%** of target geometry

3D printing rare earth magnets with PPS and **anisotropic** properties to increase strength of magnetic field

MVP and ORNL co-develop **large-scale thermoset** printer

ORNL and TechmerPM are printing **high thermal conductivity polymers** and have achieved heat conduction up to 4W/(m·K)

ChoiceSpine granted FDA clearance for 3D Printed Vertebral Body Replacement Device based on ReVV program

ORNL and industry showcase the ability to additively manufacture, machine and pull parts from **5 dies** fabricated over the course of 6 days on the **IMTS** show floor. Dies were then scanned to ensure tolerances were met.

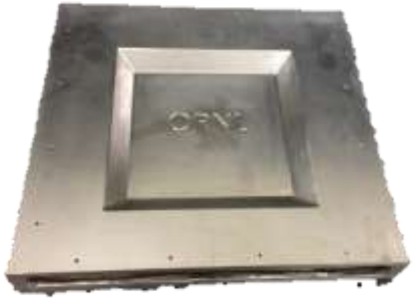
ORNL and Xzeres Wind make a composite wind blade using an additive mesh core and composite clamshell skin

Rapid Solutions and Innovation

- Rapid Prototyping and Direct Fabrication of Final Components
- Additive Manufacturing of Tooling, Die, Molds, Jigs, Fixtures, etc.
- Over one-third of U.S. tool, die, and mold establishments have gone out of business. *Source: 2012 U.S. Congressional Report*
- AM provides opportunity to fabricate tools at reduced times and costs

Prototyping

Tooling



Direct Fabrication

Hydro

Wind

Buildings

Fossil

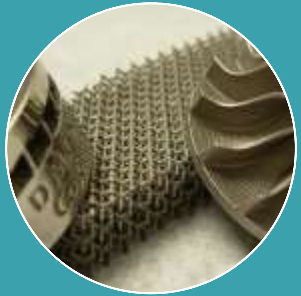
Transportation

ORNL’s Vision for Manufacturing

Vision: ORNL’s vision is to integrate additive manufacturing, machine tools, and CF/Composites Manufacturing with Artificial Intelligence, Data Analytics, Robotics, Controls and Automation to enable Manufacturing 4.0.

Additive Manufacturing
MDF

Carbon Fiber Composite
CFTF/SURF/IACMI



Intelligent Machine Tools

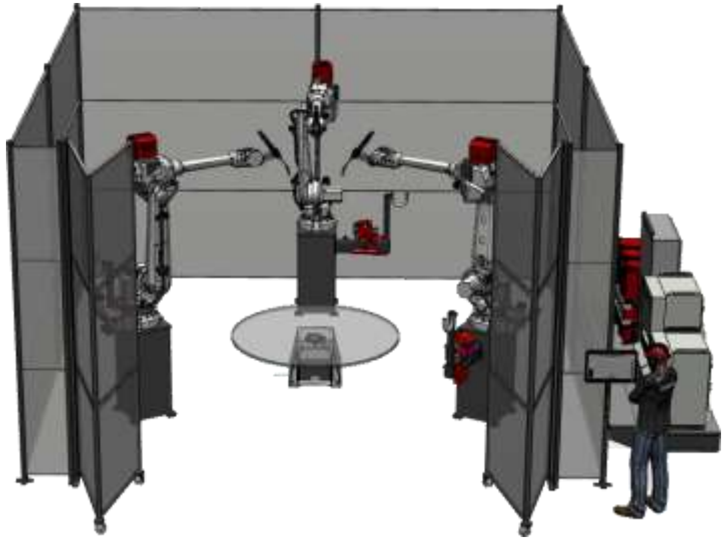
Roll to Roll Processing,
BMF

Robotics, Automation and Controls

Cyber Security/AI/Data Analytics for Manufacturing
SNS, HFIR,OLCF

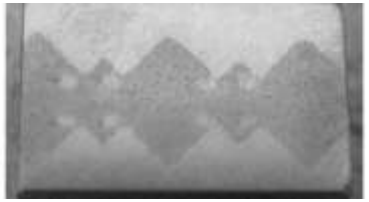
Smart & Secure Manufacturing

- The factory of the future is:
  - Automated: Extremely efficient, fast, reliable
  - Digital: Machine to machine, factory to factory, consumer to product
  - Intelligent: Optimizes workflow and predicts failure
  - Flexible: design, logistics, adapting to changes in demand
  - Multiple Material Solutions: Enable hybrid, composite, and graded structures with multiple manufacturing technologies
  - Human: Workforce converted from manual, monotonous tasks (low skill/low wage) into supervision and control tasks (high skill/high wage). Synergistic combination of human (cognitive) and machine (labor)
  - "Born Qualified": Data analytics, machine learning and AI approach to rapid low-cost certification/qualification
  - Security by design and manufacture
- End to End – Concept to product



Large Components / Systems

Real-Time Monitoring & Correction



Multiple Material Solutions

OAK RIDGE National Laboratory

Education and Training

Dr. Suresh Babu
Mechanical, Aerospace & Biomedical Eng. (Ohio State) light weight metals *additive manufacturing*

Dr. Uday Vaidya
Mechanical, Aerospace & Biomedical Eng. (UAB) *composites manufacturing*

Governor's Chairs in Strategic Areas

- 50% ORNL & 50% UTK with shared lab space
- ~54 undergrad & graduate students performing R&D in advanced manufacturing
- MAJIC IUCRC (The Ohio State University, Colorado School of Mines, the University of Tennessee, etc.)

Workforce Development

- Adv. mfg. internship with Pellissippi pilot launched: FY14 (120 inquiries, 73 applications, 25 internships)
  - 15 Army, Navy, or Marine veterans

Training Our Next Generation

- >5 years of volunteer mentorship for FIRST ROBOTICS
- >750 students engaged
- **DOE-AMO enabled 400 desktop printers 2014 FIRST Robotics** partnering with **America Makes.**

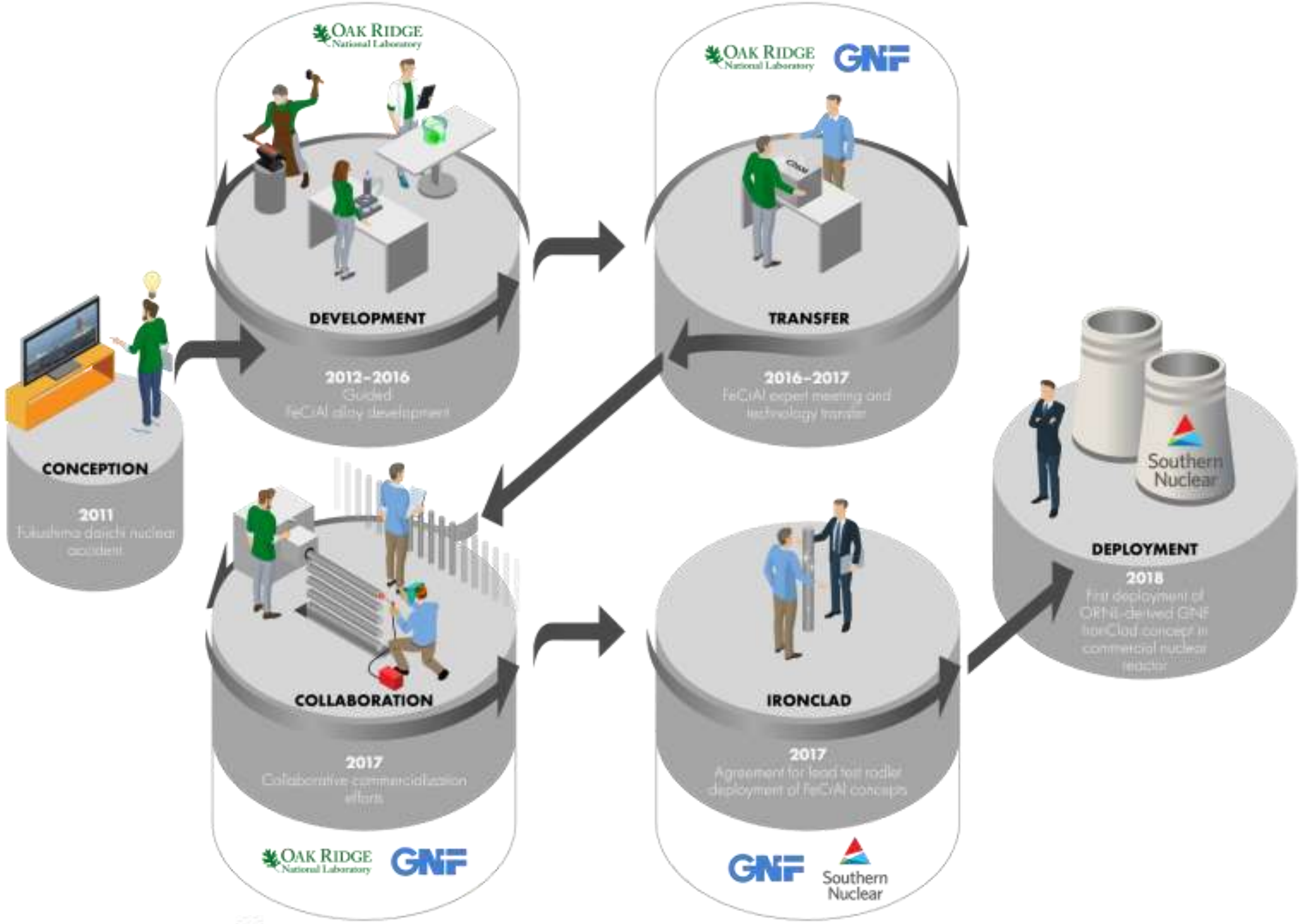
Growing Internship Program

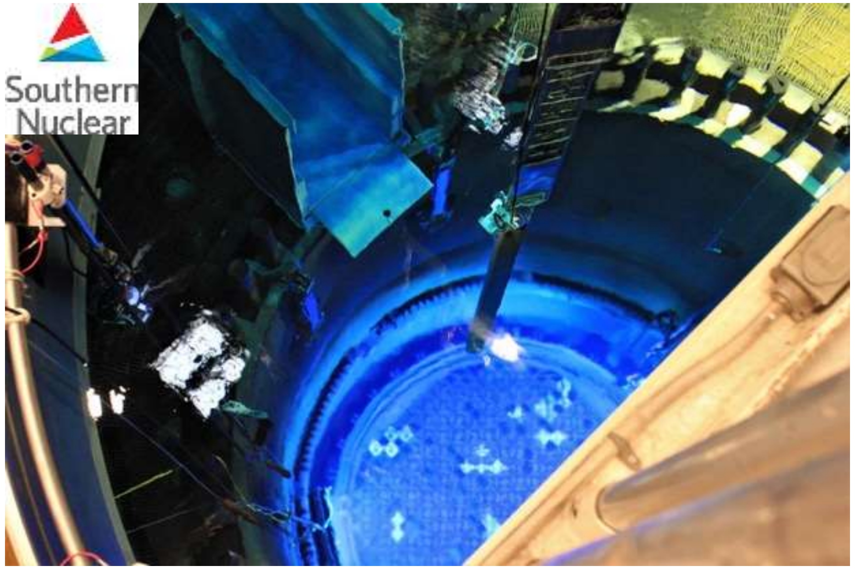
- 114 Students Summer of 2017
- Grown from 50 to over 100 Students in <4 years
- Projects include prosthetics, robotic design, hydraulics, materials characterization, AM simulation, design, etc.

>50 universities have partnered with the MDF

OAK RIDGE National Laboratory

ORNL Manufacturing Capabilities Directly supported development and Scale up of ATF Cladding





ATF FeCrAl insertion in Hatch-1
Courtesy of John Williams

Working with Oak Ridge National Laboratory

Mechanisms for enhancing, developing & improving your idea/technology

	User Agreement (non proprietary)	**Strategic Partnership Project** (Proprietary)	**Cooperative Research & Development Agreement**
Length of engagement	Up to 12 months.	As defined by agreement.	Longer-term basis of a year or more.
Cost to Company	No cost.	Full cost recovery.	Cost-share required.
Intellectual Property Rights	Each party owns its own inventions. Jointly developed inventions will be jointly owned.	Companies own intellectual property made or created using corporate funds as a result of these engagements.	Companies own inventions they make during the collaboration and have an option to negotiate an exclusive license in a specific field of use to inventions made by ORNL.
Protection of Generated Information	Information generated is publicly available.	Companies paying for services with corporate funds can treat all generated data as their proprietary information.	Commercially valuable information generated under a CRADA may be protected for up to 5 years, depending on funding source.

Final reports of select industry collaborations. ORNL Partnerships.

Technical Approach: Industry Collaborations

Explore
- Opportunity for industry to discover and apply new manufacturing technologies

Engage
- Work with MDF staff to develop scope of work

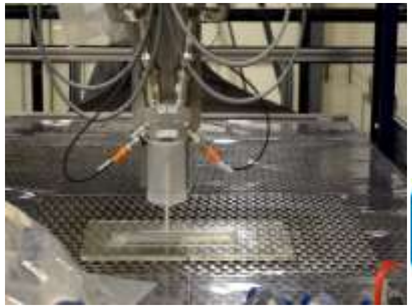
Execute
- Phase 1 $40K, Phase 2 $200K
- 1:1 Cost Match
- Non-Negotiable CRADA
- ~90-day cycle time from review to a signed agreement

Status	Phase 1	Phase 2	TOTAL
Pending Agreement	13	1	14
Active	31	6	37
Complete	79	10	89
Total	**123**	**16**	**140**

Currently **37 active** Collaborative Research and Development Agreement partners, and **140 total**

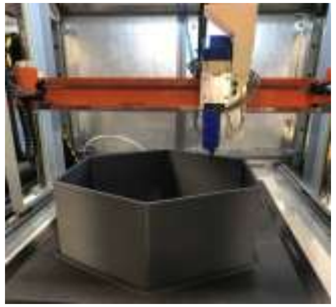
REVV! Tennessee Manufacturing Innovation Program

In addition, the state of TN Funds Research to Provide Innovation in Manufacturing



Evaluation of advanced polymers with tunable reaction kinetics for AM

PPG



Medium Area Additive Manufacturing (MAAM) for composite AM

Cosine

Using AM to fabricate small modular hydropower devices

Eck Industries, Inc.

emrgy

CMI Critical Materials Institute

OAK RIDGE National Laboratory

40 Systems and >$12M of Industry Provided Equipment

Electron Beam Melting

- Developing in-situ characterization, feedback, and control
- Heated powder bed
- Expanding range of materials (Ti64, CoCr, 625, 718)
- Precision melting of powder materials

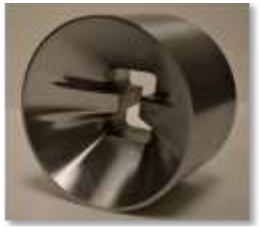
CAD TO METAL Arcam AB

Metal Wire & Powder Feedstock

- Metal wire and powder feedstock allows for improved mechanical properties and surface finishes
- Will work with advanced materials for large-scale welding such as 410ss

WOLF ROBOTICS LINCOLN ELECTRIC America Makes

Laser Metal Deposition



- Site-specific material addition
- Application of advanced coating materials for corrosion and wear-resistance
- Repair of dies, turbines, etc.

POM DM3D

Selective Laser Melting

- Unheated powder bed
- Wide range of material choices (316L, 17-4PH, H13, Al, Ti, 718, 625)
- Precision melting of metal powders
- Up to 630 x 400 x 500mm build volume

RENISHAW CONCEPTLASER SLM

Metal Binder Jetting

- Metal matrix composites and sintered materials including:
- Stainless steel + bronze
- Tungsten + titanium
- Ceramics + sand
- Large build volumes (10 x 10 x 16in)
- Fast build times (30 sec/layer)

ExOne

Large-Scale Welding

- Open-air environment
- MIG welding arm with 6 DOF and 2 rotational degrees
- Print size not restricted
- Uses low-cost welding torches and wire
- CAD-to-path functionality

WOLF ROBOTICS LINCOLN ELECTRIC

New facility 110,000 sq. feet total with 40,000 sq. feet of high bay

Large-Scale Laser Metal

- Reducing buy-to-fly ratio of aerospace components
- Using 4kW laser and two 10kW lasers to melt Ti64 wire
- Inert system with argon-filled tent
- Prints ~10cubic inches/hr.

Oak Ridge National Laboratory

Hot Isostatic Press

- First rapid-quench HIP in America
- 180mm diameter
- Can reach pressures of 25,000psi
- Cooling rates of 3000C/min when cooled from 3000C
- Can HIP and heat treatment in same cycle

Quintus

Large-Scale Polymer Deposition

- Deposits up to 1000lbs. of pellet feedstock material per hour
- Build volume up to 20' long x 6' wide x 8' tall
- Printed >37 different polymers and composites
- Dual material capabilities

CINCINNATI

Ingersoll Large-Scale Polymer Deposition

- Under development
- Will have 46' x 23' x 10' build volume
- Target deposition rate of 1000 lbs./hr.
- Will be 10x larger and faster than previous commercial systems

INGERSOLL Machine Tools

Thermoset Dual Material Extrusion

- Capable of depositing 300mL/minute
- Can control material properties and speed on the fly
- Cross-linking between layers
- 2-part resin

ShopBot PPG

Large-Scale Thermoset Deposition

- 16' x 8' x 3.5' build volume
- 4 axes + coordination with pumping system
- Can print up to 50"/second depending on material
- 2-part resin

MVP

Partnering with Industry

*Over **180** industry partners*

Material Suppliers	Equipment Suppliers	End Users

Material Suppliers
- TECHMER PM Polymer Modifiers
- ResourceFiber Bamboo Fiber for Industry
- sabic
- CARPENTER
- ATI
- CHOMARAT
- Polynt
- AvCarb
- American Chemistry Council
- ALCOA
- ARCONIC Innovation, engineered.
- TECHMER ES Engineered Solutions
- NRG: The CMU Designed for Today — Save Labor. High Performance. Continuous Insulation.
- PLASTECH CORPORATION
- SAINT-GOBAIN
- BASF
- EASTMAN Eastman Chemical Company

Equipment Suppliers
- GKN AEROSPACE
- CAD TO METAL Arcam AB
- FABRISONIC
- ExOne
- WOLF ROBOTICS
- CINCINNATI Cincinnati Incorporated
- Quintus Technologies
- HYBRID Manufacturing Technologies
- GRID LOGIC
- MVP Magnum Venus Products
- Ajax Tocco
- RENISHAW
- DM3D
- Impossible Objects
- Cosine
- optonicus
- SENVOL
- SLM Solutions
- voxel
- KAWNEER
- TRANSCEND ROBOTICS
- AGCO
- PRINTSPACE 3D
- ITAMCO

End Users
- Local Motors
- Whirlpool
- Ford
- PPG
- EPRI Electric Power Research Institute
- faurecia
- Alliance
- Solar Turbines — A Caterpillar Company
- PRAXAIR
- Honeywell
- HTS IC
- Brayton Energy LLC
- emrgy
- United Technologies Research Center
- EATON
- ARNOLD Magnetic Technologies
- BOEING
- Planetary Systems Corporation
- GATE Precast Company
- AAM
- Radio Systems Corporation
- NORTHROP GRUMMAN
- gti
- AMJET Turbine Systems, LLC
- HAYNES International
- Tru Design
- Eck Industries, Inc. Specialists in Premium Aluminum Castings
- GE
- Q
- DIVERSIFIED TOOLING GROUP
- DELTA
- BWXT
- CO.LAB
- DTS Dienamic
- RIDGE
- Cummins
- HONDA
- HOVER ENERGY

>21,300 visitors total

>3,200 companies

Dozens of workshops and public outreach events

56 industry fellows

Innovation Crossroads Program
Yellowstone Energy Company Overview

Molten Nitrate Salt Reactor (MNSR)

Innovation Crossroads Program

- Lab embedded entrepreneurship program supported by AMO
- 2 year fellowships and $200-350k to work with ORNL
- Yellowstone is member of 1st cohort

Yellowstone Energy is designing a modular molten nitrate salt cooled reactor with integrated thermal energy storage to meet future market demands

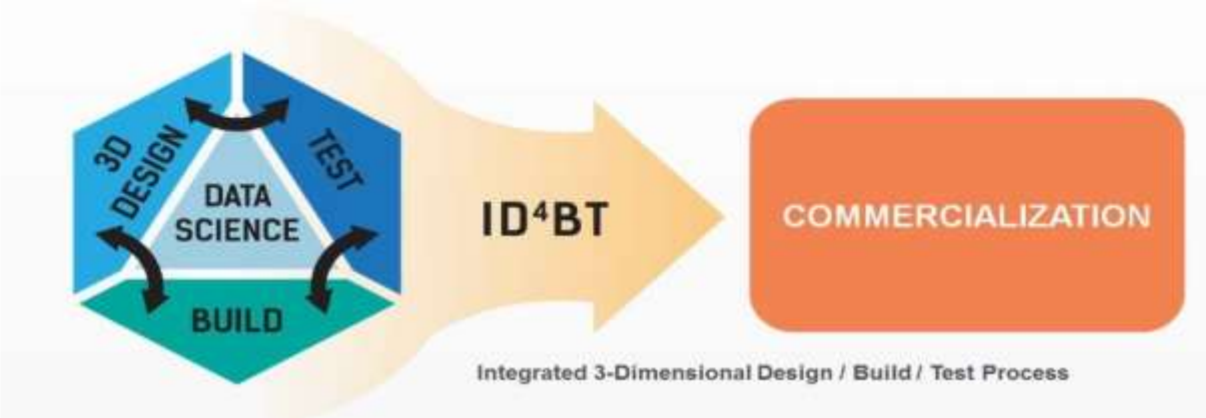
Key Differentiators

- Only advanced reactor to use commercially available nuclear fuel
- Molten nitrate salt coolant used extensively in concentrated solar power and chemical industries
- Seamlessly integrates thermal energy storage into plant design

Office of Nuclear Energy under the GAIN initiative provides an excellent pathway to collaborate with MDF on nuclear energy related projects

Two mechanism are available to industrial partners:

- NE Vouchers
- Industry FOA



FOA Awarded in FY-18:
Establishment of an integrated advanced manufacturing and data science driven paradigm for advanced reactor systems

Questions?

Oak Ridge National Laboratory
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
ADVANCED MANUFACTURING OFFICE